

Applicability of Nacelle Anemometer Measurements for Use in Turbine Power Performance Tests

Preprint

B. Smith and H. Link
National Renewable Energy Laboratory

G. Randall and T. McCoy
Global Energy Concepts, LLC

*To be presented at the American Wind Energy
Association (AWEA) WINDPOWER 2002 Conference
Portland, Oregon
June 2-5, 2002*



NREL

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

APPLICABILITY OF NACELLE ANEMOMETER MEASUREMENTS FOR USE IN TURBINE POWER PERFORMANCE TESTS

**Gordon Randall and Tim McCoy
Global Energy Concepts, LLC
5729 Lakeview Dr. NE, Suite 100
Kirkland, WA 98033
USA**

**Brian Smith and Hal Link
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401
USA**

ABSTRACT

Collection of accurate wind speed data is one of the more problematic elements in conducting wind turbine power performance tests. IEC 61400-12 specifies meteorological tower placement between two and four rotor diameters upwind of the test turbine. However, use of an upwind meteorological tower can be difficult at some sites. In some cases, complex terrain near the turbine may make placement of an upwind tower impossible. In addition, purchase and erection of a meteorological tower can be expensive, particularly as the hub height of large turbines increases.

Because of these concerns, wind farm owners and turbine manufacturers have expressed interest in the use of turbine nacelle-mounted anemometers for collection of wind speed data. The most significant problem with this practice is that wind flow is disturbed by the rotor and nacelle, so wind speed measurements collected by an anemometer mounted at the back of the nacelle do not accurately represent free-stream wind speeds experienced by the rotor. This problem can be addressed if the measurements can be adjusted; however, in order to perform such an adjustment, data must be collected to describe the relationship between the free-stream wind speeds at the rotor and nacelle anemometer. Such data collection would typically involve erecting an upwind meteorological tower, which is the specific activity that nacelle anemometer wind speed measurements intend to avoid.

The U.S. Department of Energy (DOE)-Electric Power Research Institute (EPRI) Wind Turbine Verification Program (TVP) has performed data collection and power performance tests at a number of wind energy facilities located in the United States. These activities include long-term measurements of hub-height wind speed from upwind meteorological towers and from nacelle anemometers. The purpose of this paper is to evaluate the data gathered from the Big Spring, Texas; Algona, Iowa; and Springview, Nebraska, facilities to determine whether a meaningful relationship can be derived between meteorological-tower and nacelle-anemometer wind speed measurements for Vestas V47 and V66 turbines (Big Spring) and Enron Z-50 turbines (Algona and Springview).

INTRODUCTION

As part of the U.S. Department of Energy/Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP), Global Energy Concepts (GEC) and the National Renewable Energy Laboratory (NREL) have been engaged in planning and conducting third-party power performance tests at most of the TVP project sites in accordance with the International Electrotechnical Commission (IEC) Standard 61400-12 [1]. Results of these tests have been reported at the last two WindPower conferences. [2] [3] The TVP is a joint effort between DOE, EPRI, host utilities, and developers to evaluate early production models of advanced wind turbines and to verify the performance, reliability, maintainability, and cost of new wind turbine designs and system components in a commercial environment.

An objective of the TVP power performance testing was to exercise the IEC standard and gain experience with the specified methodology and procedures. One of the more problematic elements of the testing is the ability to meet the requirements for meteorological (MET) tower placement in complex terrain in order to obtain accurate representation of the wind resource experienced by the test turbine rotor. For several of the TVP tests, the sites did not meet the topographic requirements specified in the IEC standard. In such cases, the standard requires a site calibration, which involves the installation of a second hub-height MET tower at the turbine site before the turbine is installed. For many wind projects, the time and cost of conducting a site calibration is not practical. In addition, it may not be possible to place a MET tower at the IEC-specified upwind distance of two to four rotor diameters from the test turbine at some sites because of terrain limitations. The most recent addition to the TVP, the Buffalo Mountain wind project owned by the Tennessee Valley Authority (TVA), provides a good example of these issues. The three Vestas V47 turbines in the Buffalo Mountain project are located in a rugged mountainous area and the terrain drops off severely in all directions, prohibiting the placement of a MET tower in the vicinity of the turbines.

To address these issues, a number of wind industry members have promoted the use of data from nacelle-mounted anemometers to generate wind speed measurements for power performance testing. Assuming an accurate methodology can be established, there are several advantages to this concept. Wind turbines are already equipped with nacelle anemometers and additional equipment purchases may be limited, thus reducing the overall cost of testing. In addition, the approach offers an option for evaluating turbine performance in complex terrain where MET tower placement may be difficult.

However, there are also significant drawbacks to the use of nacelle anemometers for power performance testing. Nacelle anemometers do not accurately represent the free-stream wind speeds experienced by the rotor due to their mounting location (behind the rotor on upwind wind turbines) and the impact of the nacelle structure and blades on the wind flow. Figure 1 shows examples of anemometers on a MET tower and on a wind turbine nacelle. In order to account for these impacts, wind data from the nacelle anemometers must be adjusted to represent the free-stream wind flow seen by the rotor. Another disadvantage is that nacelle anemometers are typically not calibrated, introducing additional uncertainty into the testing process.

Because detailed data is available from each of the TVP projects (including nacelle anemometer readings) and because power performance tests have already been conducted at these sites, the TVP is in a unique position to evaluate the use of nacelle anemometers for power performance tests. In addition, the TVP is interested in such methods as a potential performance evaluation tool for the TVA Buffalo Mountain project where testing in accordance with the IEC standard is not possible.

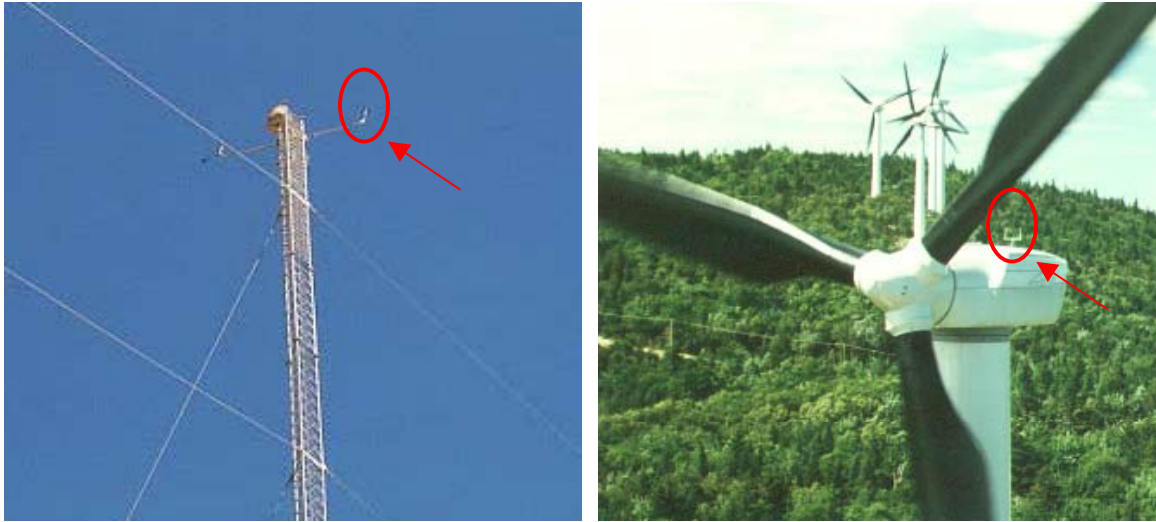


FIGURE 1: MET TOWER AND TURBINE NACELLE ANEMOMETERS

In this paper, data from three TVP wind projects—Big Spring, Texas, Algona, Iowa, and Springview, Nebraska—were evaluated to establish relationships between free-stream wind speeds measured by upwind MET towers and wind speeds measured by nacelle anemometers. Relationships determined for individual turbines were then applied to other turbines of the same type to determine whether the results were replicable.

The location of these projects is shown in Figure 2 [4]. Three wind turbine models were included in this analysis: Vestas V47 and V66 turbines in Texas and Enron Wind Z-50 turbines in Iowa and Nebraska. Power performance tests in accordance with the IEC standard have been performed on all but one of the turbines selected for evaluation in this analysis [2] [3]; the remaining turbine did not undergo a formal power performance test but has an upwind MET tower suitable for performance of such a test.

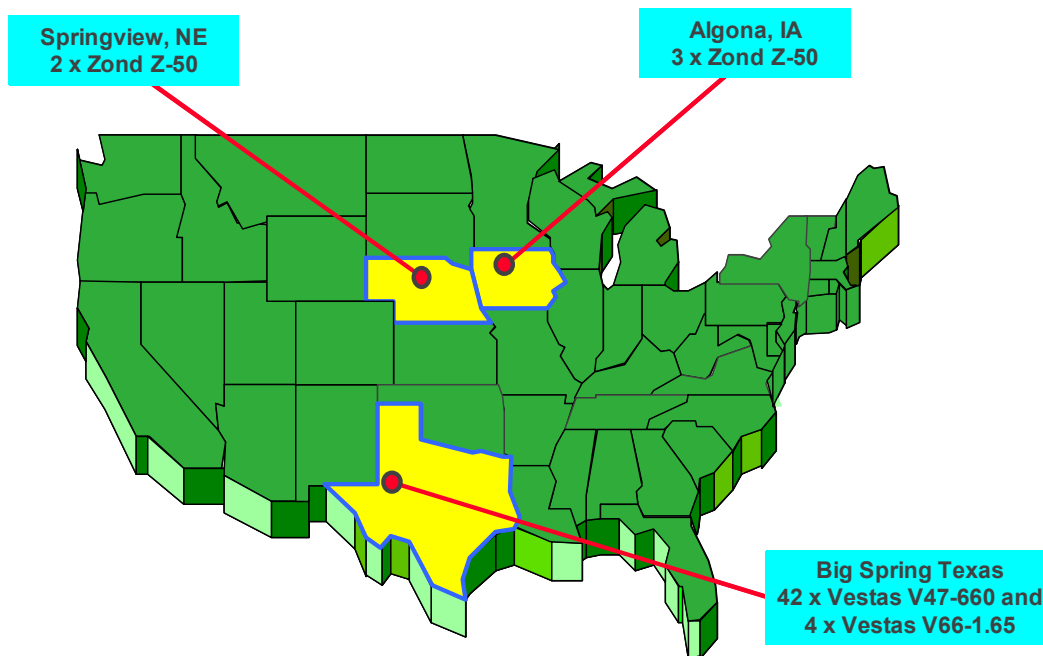


FIGURE 2: TVP PROJECT LOCATIONS

METHODOLOGY

A consistent procedure was used to evaluate the MET tower and nacelle anemometer data examined in this paper. The methodology is outlined below:

1. For each turbine model, a “primary” turbine was selected for analysis. For each primary turbine, a successful power performance test had previously been conducted using an upwind MET tower in accordance with the IEC standard. These baseline turbines included V47 Turbine 26 and V66 Turbine B at the Big Spring project, and Z-50 Turbine 3 at the Iowa project.
2. For two turbine models, a second turbine was selected to evaluate the accuracy of relationships developed at the primary turbine. Nebraska’s Z-50 Turbine 1 was selected as a “second” turbine because a power performance test had also previously been conducted on that turbine. Big Spring’s V47 Turbine 40 was selected as a “second” turbine because an upwind MET tower was currently in place. An appropriate “second” V66 turbine was not identified.
3. For each of the primary turbines, a period of data was selected where both valid MET tower wind speed and nacelle anemometer wind speed measurements were available. If possible, these data were selected from a time period immediately preceding or following the power performance test. The objective was to verify whether relationships observed for these turbines were consistent over time, given the same measurement equipment. In some cases, the data analysis period overlapped with the power performance test period due to insufficient readily available data from other times.
4. The selected MET tower and nacelle anemometer wind speed data were processed using methods consistent with the IEC Standard to the extent possible. For example, invalid direction sectors were established consistent with the Standard’s guidelines and only data from unobstructed direction sectors were used. Data were also excluded for periods of icing and when the turbine was offline. One deviation from the standard was that data from below cut-in wind speeds were excluded from evaluation in this analysis in order to minimize errors from use of offline data. Finally, wind speed data were normalized to a sea-level air density of 1.225 kg/m^3 using equation 5 from the Standard.
5. Remaining MET tower and nacelle anemometer wind speed data were plotted against each other and a linear trendline describing the relationship between the measurements was determined. Other methods of describing the relationship, such as binned ratios and a third-order regression, were also examined.
6. The relationships were then applied to nacelle anemometer measurements for each turbine to generate nacelle anemometer-based power curves. Results from the nacelle anemometer-based tests were directly compared with the previously conducted power performance tests, when possible.
7. Power curves from the MET tower and nacelle anemometer were compared in two manners. First, the two curves were plotted atop each other to determine if the power curve based on the nacelle anemometer fell within the uncertainty estimates of the MET tower curve (as determined during the earlier power performance test) throughout most or all of the curve. Second, the annual energy production (AEP) for the turbine was calculated using each power curve for an assumed annual average wind speed of 8 m/s and a Rayleigh distribution.

Wherever possible, the analyses were performed in accordance with the IEC Standard. Calibrated MET tower anemometers were available for all tests, but the nacelle anemometers were not calibrated; this is a deviation from the Standard. In addition, the locations of the V47 and V66 turbines at the Big Spring project and the Z-50 turbine at the Nebraska did not meet the

topographic requirements specified in the Standard and no site calibration was practical. However, evaluation performed as part of the power performance tests at the Big Spring turbines indicated that the topographic variations did not appear to have a significant effect on the power curves. Other minor deviations from the Standard included a lack of hub height temperature and pressure sensors; hub-height temperature and pressure were estimated from lower-level measurements.

TEST RESULTS

The results of the analyses, including power curve and AEP comparisons, are presented in this section for five cases. Additional observations and conclusions are discussed following the results.

Case 1: Big Spring V47 Turbine 26

Wind speed data generated from V47 Turbine 26 during a time period immediately preceding the turbine's power performance test were used to generate the relationship between the MET tower and nacelle anemometer measurements for the V47. Figure 3 illustrates the observed relationship. Only limited scatter is apparent, and a linear relationship is seen from wind speeds at cut-in up to approximately 15 m/s. Above 15 m/s, the relationship appears to vary from linear.

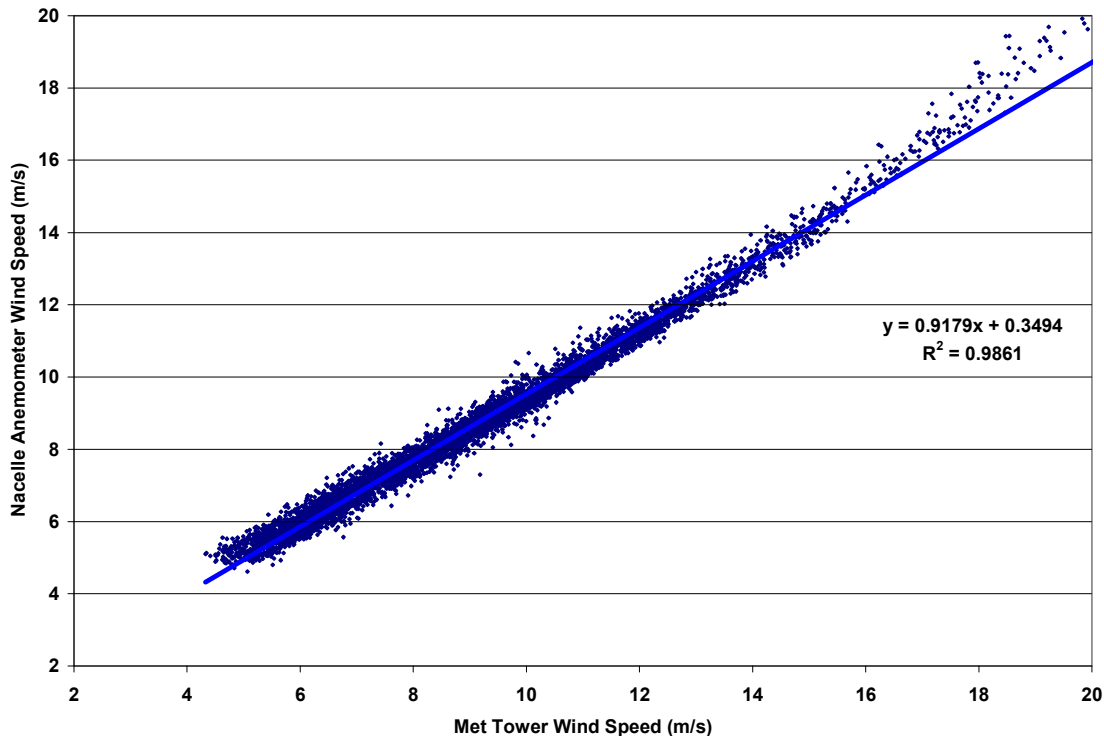


FIGURE 3: RELATIONSHIP BETWEEN MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, BIG SPRING VESTAS V47 TURBINE 26

This relationship was applied to nacelle anemometer wind speed measurements from the period of the power performance test. Figure 4 presents scatter plots of power vs. wind speed measurements for this turbine based on the MET tower and nacelle anemometer measurements. Throughout the body of the curve, there is much less scatter in the power measurements using the nacelle anemometer to generate wind speeds than using the MET tower data. This is also reflected in the standard deviations of the points in each wind speed bin. Up to approximately 11 m/s, the standard deviations in the bins using the nacelle anemometer results are about 40% lower

than using the MET tower results. This indicates that the nacelle anemometer may provide much more precise estimates of free-stream wind speeds at the rotor, although these estimates may be less accurate.

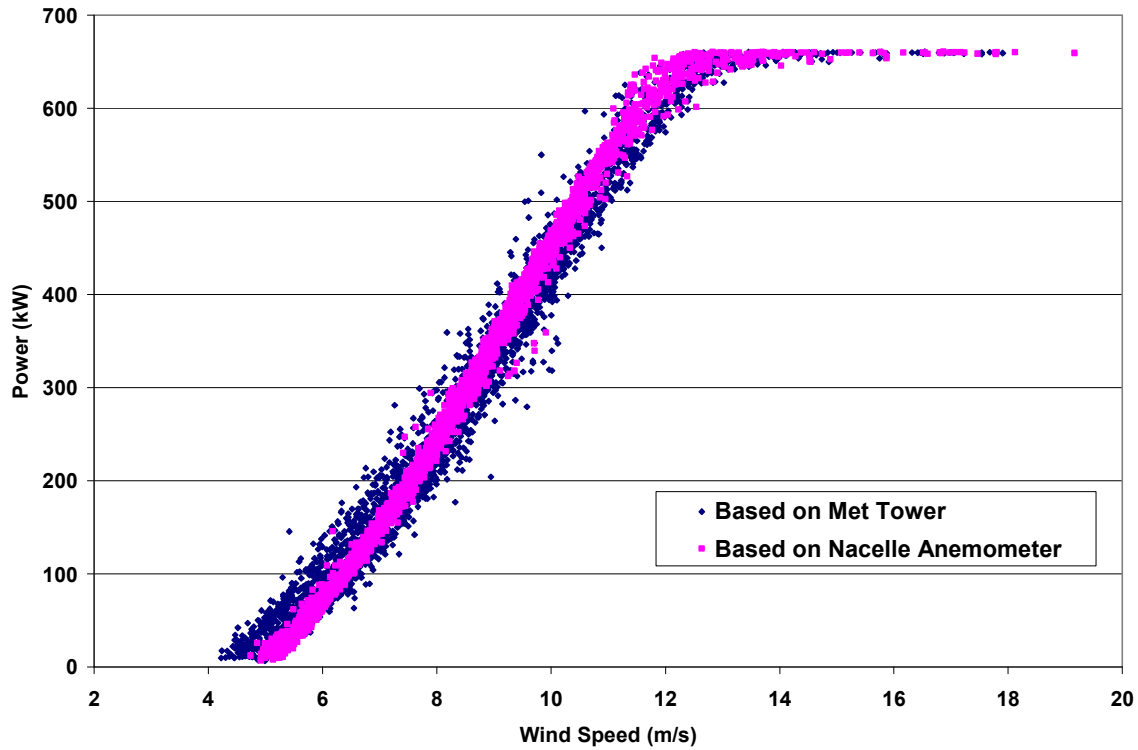


FIGURE 4: SCATTER PLOT OF POWER VS. WIND SPEED, BIG SPRING VESTAS V47 TURBINE 26

The calculated power curves for Big Spring V47 Turbine 26 are presented in Figure 5. As shown, the power curve based on the nacelle anemometer falls within the uncertainty estimates of the curve based on the MET tower (shown as error bars off the measurement points). The power curve based on the nacelle anemometer appears to overestimate power by several percent between approximately 8 m/s and 12 m/s and underestimates power slightly below 6 m/s. The AEP was calculated for each curve using an average annual wind speed of 8 m/s, with results of approximately 2.22 GWh/year for the power curve based on the MET tower and 2.25 GWh/year for the power curve based on the nacelle anemometer. These results differ by approximately 1.4%.

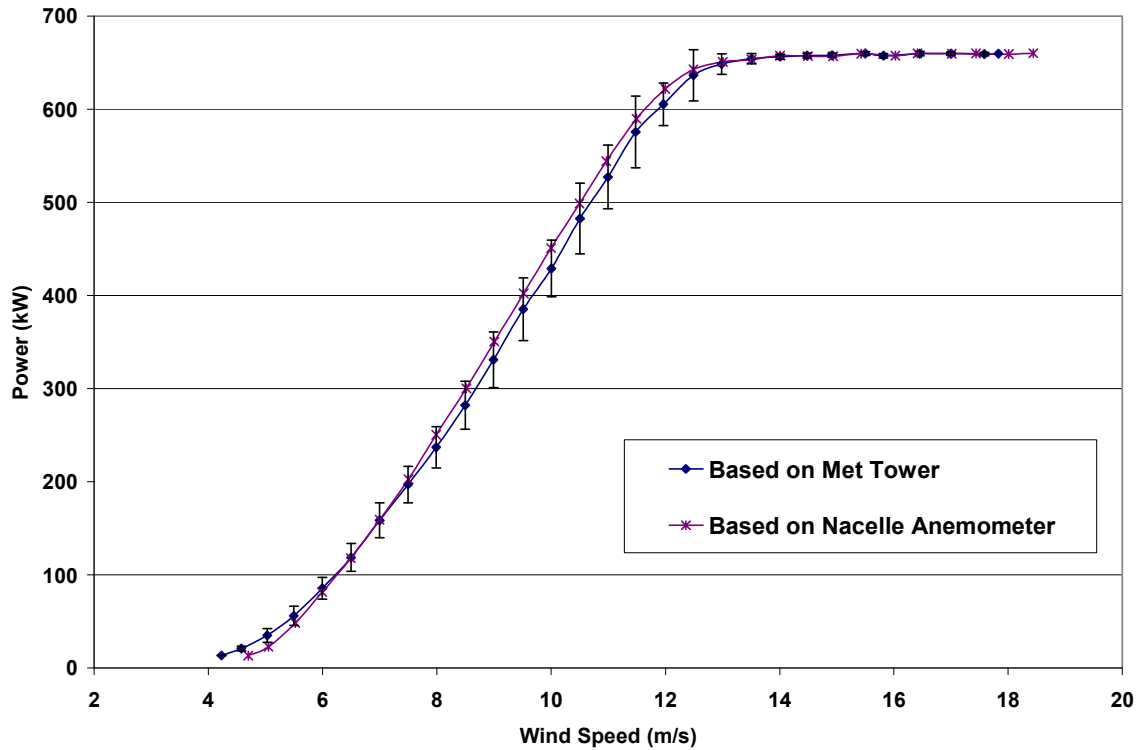


FIGURE 5: COMPARISON OF POWER CURVES, BIG SPRING VESTAS V47 TURBINE 26

Case 2: Big Spring V47 Turbine 40

The relationship between MET tower and nacelle anemometer wind speeds determined for Big Spring V47 Turbine 26 in Case 1 was applied to Turbine 40, located approximately four miles to the east in similar terrain, and power curves were generated for this turbine. Because no complete power performance test has been conducted on Turbine 40 and because the measurement equipment available for this turbine does not meet the requirements of the Standard, uncertainty estimates for the power curve were not available. Deviations from the IEC standard include the lack of temperature or pressure data at the MET tower (sensors from other towers were used as surrogates), a calibrated power transducer was not installed at the turbine, and topographic assessments were not conducted. Nonetheless, there are no apparent indications that the uncertainties associated with the data from this turbine are significantly greater than those shown for Turbine 26.

The two power curves are shown in Figure 6. The power curve based on the nacelle anemometer is significantly lower than the curve based on the MET tower between about 10 m/s and 14 m/s, with a maximum difference of 30 kW (about 5%) around 12 m/s. The results are higher than the curve based on the MET tower between approximately 6 m/s and 9 m/s. The AEP was calculated for each curve using an average annual wind speed of 8 m/s, with results of approximately 2.24 GWh/year for the power curve based on the MET tower and 2.23 GWh/year for the power curve based on the nacelle anemometer. These results differ by approximately 0.3%. In this case, although there may be errors of several percent in varying directions for each wind speed bin, these errors essentially cancel each other out when calculating the AEP.

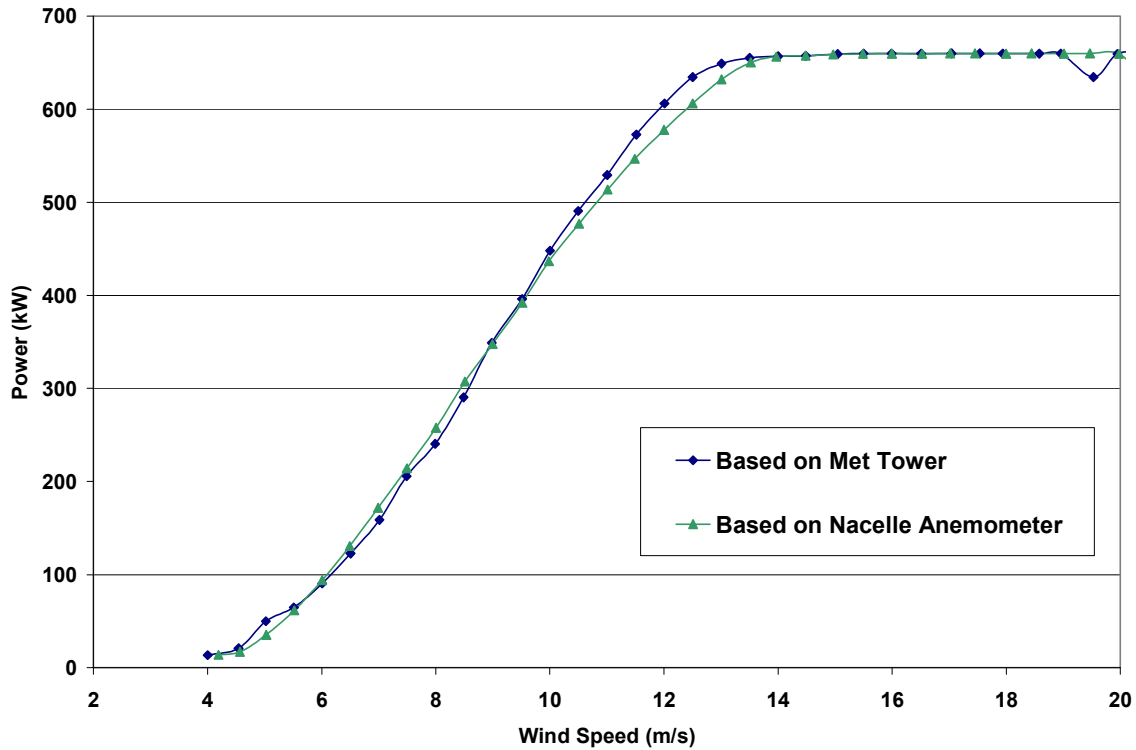


FIGURE 6: COMPARISON OF POWER CURVES, BIG SPRING VESTAS V47 TURBINE 40

Case 3: Big Spring V66 Turbine B

Wind speed data generated from V66 Turbine B during a time period immediately preceding the turbine's power performance test were used to generate the relationship between the MET tower and nacelle anemometer measurements for the V66. This relationship was applied to nacelle anemometer wind speed measurements from the period of the power performance test. The calculated power curves for this turbine are presented in Figure 7. As shown, the curves are reasonably close, with the curve based on the nacelle anemometer falling within uncertainty estimates on the curve based on the MET tower. However, the curve based on the nacelle anemometer is somewhat lower between wind speeds of about 8 m/s to 12 m/s. The AEP was calculated for each curve using an average annual wind speed of 8 m/s, with results of approximately 4.51 GWh/year for the power curve based on the MET tower and 4.40 GWh/year for the power curve based on the nacelle anemometer. These results differ by approximately 2.5%.

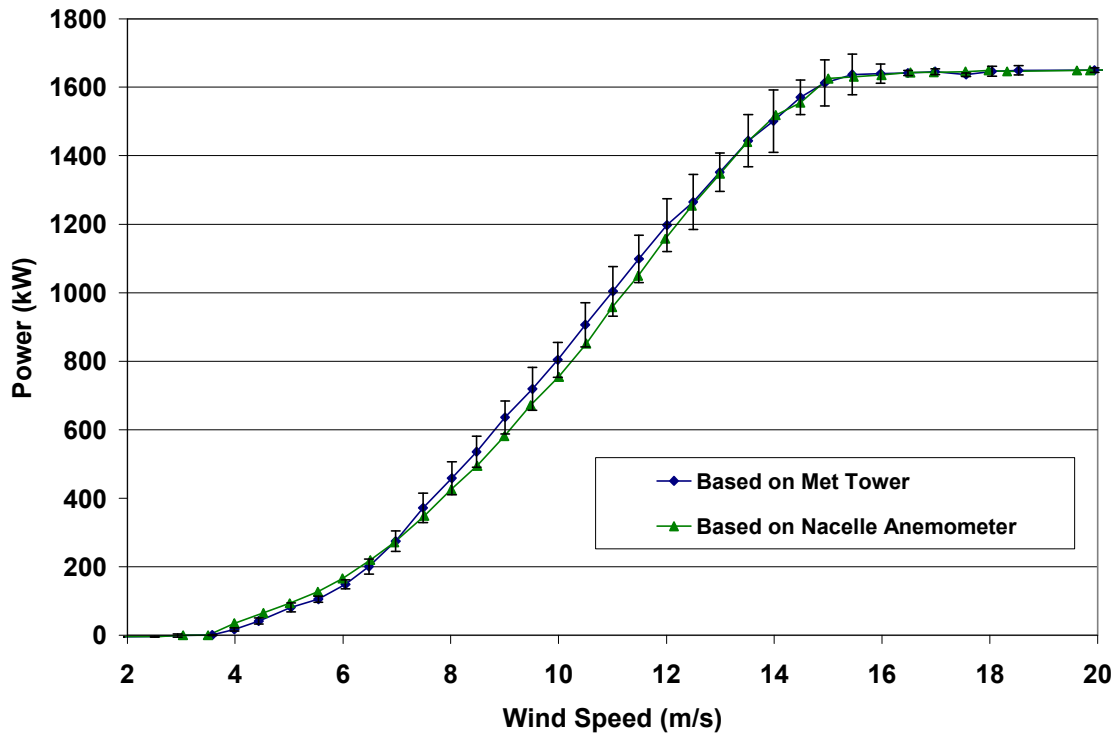


FIGURE 7: COMPARISON OF POWER CURVES, BIG SPRING VESTAS V66 TURBINE B

Case 4: Iowa Z-50 Turbine 3

Wind speed data generated from Iowa Z-50 Turbine 3 during a time period around and during the turbine's power performance test were used to generate the relationship between the MET tower and nacelle anemometer measurements for the Z-50. Figure 8 illustrates the observed relationship. Some scatter is apparent at low wind speeds, but the relationship appears generally linear across the range of measurements.

Unlike the results for the V47 shown in Figure 3, the slope of this relationship exceeds 1, indicating that the nacelle anemometer wind speed measurements are reported as being higher than at the upwind MET tower. There are several possible reasons for this. It is possible that winds are affected by the nacelle of the Z-50 in a manner that produces increased wind speeds at the anemometer. It is also possible that a scaling factor may be applied to the measurements through turbine programming for control purposes. The specific reason this may occur is not crucial to understand, as long as the reason is the same across turbines (i.e., if a scaling factor is being applied through the turbine controller, it is important that the same scaling factor be applied in all turbine controllers for which the observed relationship may be applied).

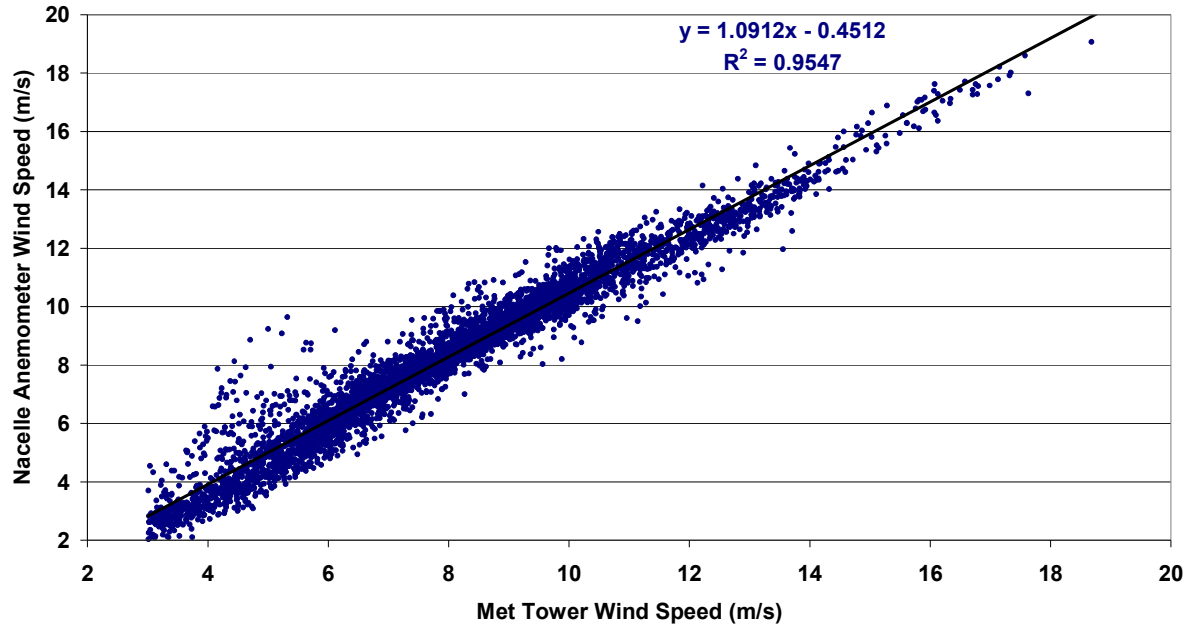


FIGURE 8: RELATIONSHIP BETWEEN MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, IOWA Z-50 TURBINE 3

The calculated power curves for Iowa Z-50 Turbine 3 are presented in Figure 9. The modified nacelle anemometer power curve is within the uncertainty bounds of the MET tower curve (shown as error bars on the curve) over all wind speeds. The AEP was calculated for each curve using an average annual wind speed of 8 m/s, with results of approximately 2.51 GWh/year for the power curve based on the MET tower and 2.49 GWh/year for the power curve based on the nacelle anemometer. These results differ by approximately 1.1%.

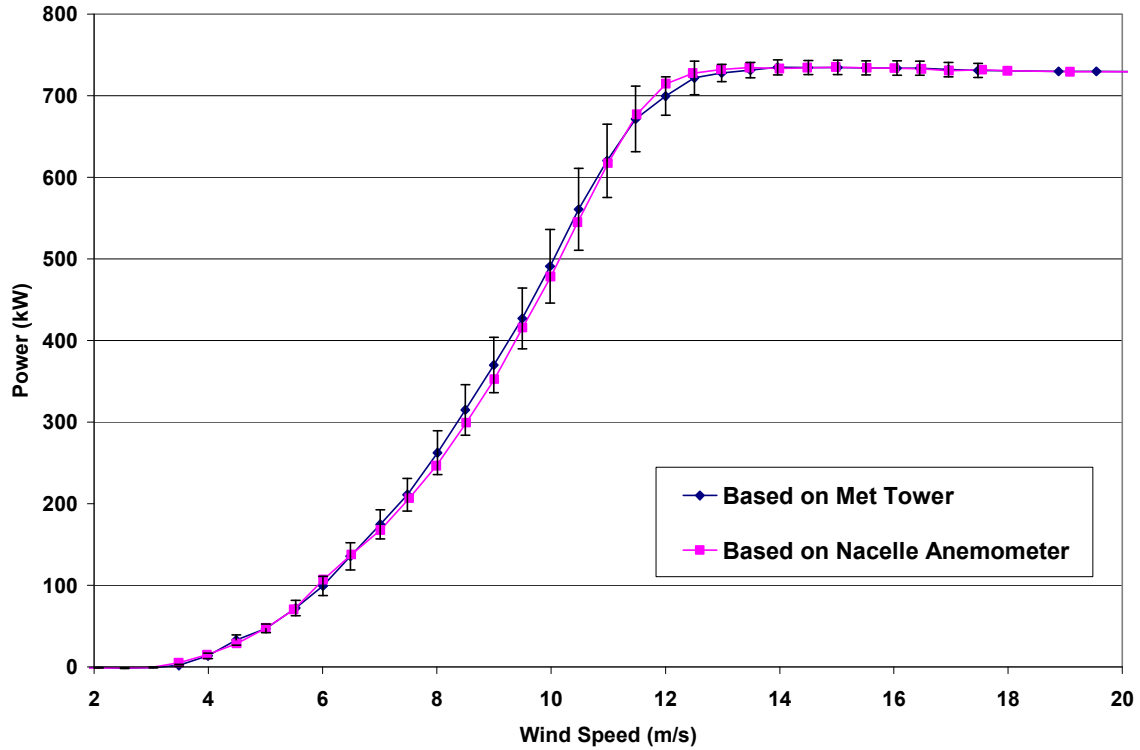


FIGURE 9: COMPARISON OF POWER CURVES, IOWA Z-50 TURBINE 3

The scatter in the power curve was also evaluated. As with the V47 results shown in Figure 4, there is much less scatter in the power measurements based on nacelle anemometer than using the measurements based on the MET tower, with the exception of some points off the curve at low wind speeds. The standard deviations in each wind speed bin are about 30% to 40% lower throughout the body of the curve using the nacelle anemometer.

Case 5: Nebraska Z-50 Turbine 1

The relationship between MET tower and nacelle anemometer wind speeds determined for Iowa Z-50 Turbine 3 in Case 4 was applied to Nebraska Z-50 Turbine 1. The resulting power curves for this turbine are presented in Figure 10. The curve based on the nacelle anemometer power curve is slightly lower than the MET tower curve from approximately 6 m/s to 12 m/s, and it also exhibits a slight “dip” above rated wind speed at which a few erroneous high nacelle anemometer wind speed measurements are influencing the bin averages. However, the body of the curve is within the uncertainty on the curve based on the MET tower. The AEP was calculated for each curve using an average annual wind speed of 8 m/s, with results of approximately 2.45 GWh/year for the power curve based on the MET tower and 2.39 GWh/year for the power curve based on the nacelle anemometer. These results differ by approximately 2.6%.

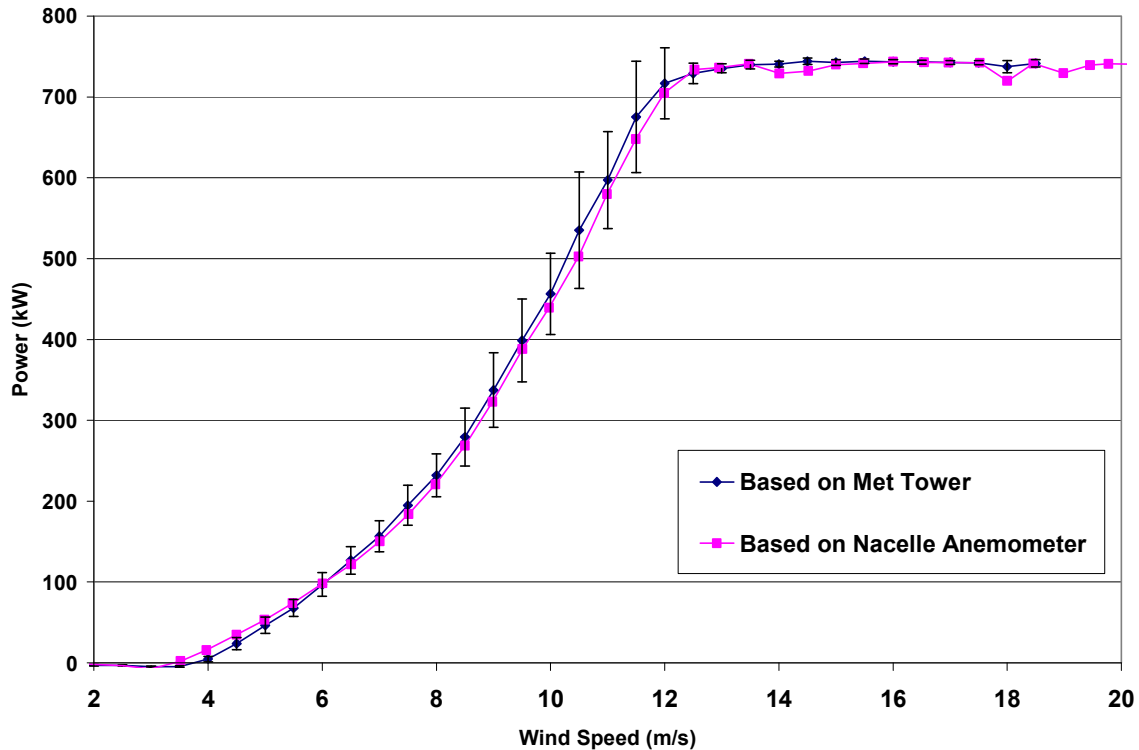


FIGURE 10: COMPARISON OF POWER CURVES, NEBRASKA Z-50 TURBINE 1

ADDITIONAL OBSERVATIONS

In addition to the results above, supplementary investigations were conducted as part of this work to better understand the analyses and the technical implications of the results. Specific data sets available at some sites provided an opportunity to further examine some interesting technical considerations. These observations and indicative analyses are discussed below.

Use of off-line data for determining relationships

As previously noted, only online turbine data from periods when energy was generated were used to determine the relationships between MET tower and nacelle anemometer wind speeds. Additional analyses were conducted to determine the impact of using data from when the turbines were not running.

Figure 11 presents the difference in observable relationships between when V66 Turbine B was online and operating versus when the turbine was not running (i.e., faulted, paused, or in maintenance mode). As shown, there is a significant difference in these relationships, with a slope varying by more than 0.13 between the two cases. One explanation for these results is that wind flow behind the rotor will be much different when the turbine is not operational; however, there may be additional contributing effects. For example, the turbine may not be yawed into the wind if faulted, and it may therefore expose the nacelle anemometer to the wind from a different direction.

It should be noted that while these results support the use of only online data when determining relationships between MET tower and nacelle anemometer wind speeds, this practice may increase uncertainties in cases in which offline data are to be used in power performance tests,

such as if the turbine goes offline for normal turbine control reasons. Such occurrences are likely to be rare, so the increase in uncertainties should be negligible for most turbines.

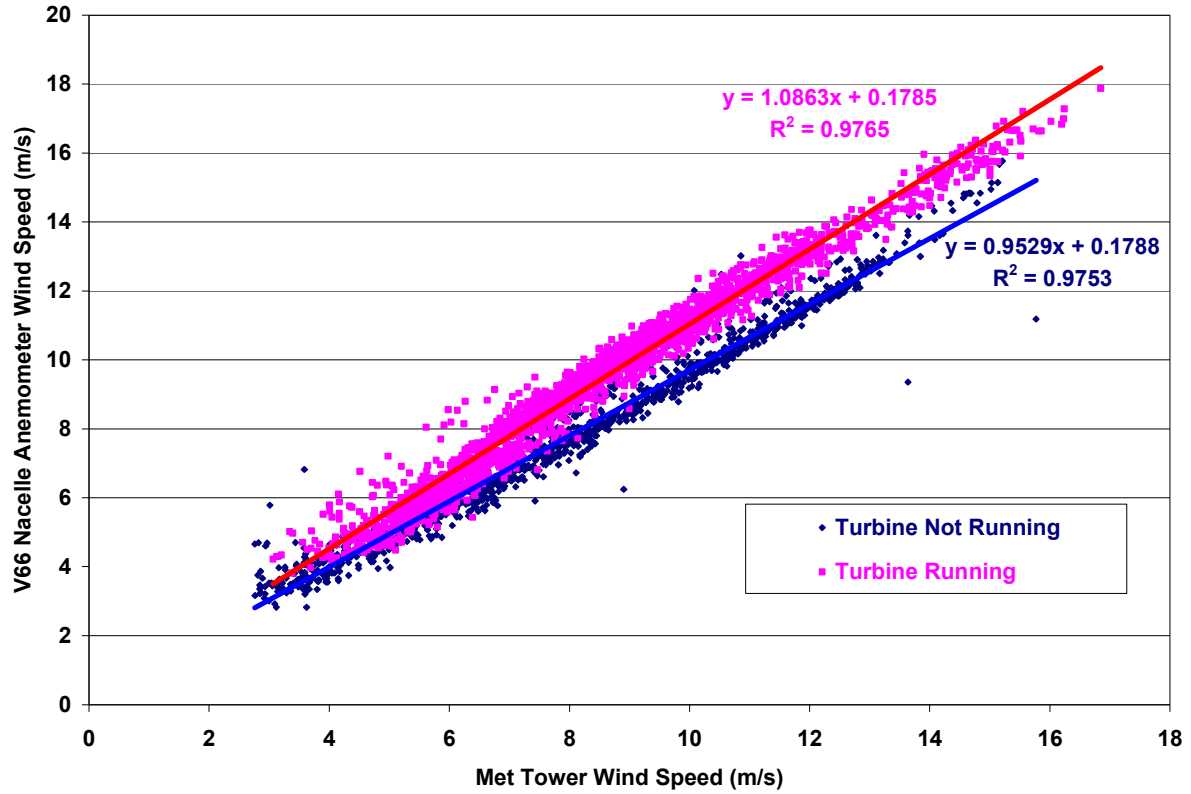


FIGURE 11: COMPARISON OF RELATIONSHIPS BETWEEN MET TOWER AND NACELLE ANEMOMETER WHEN V66 IS RUNNING AND NOT RUNNING

Anemometer Calibration Issues

As noted earlier, none of the nacelle anemometers used in this evaluation were calibrated. To investigate the uncertainties associated with the use of uncalibrated anemometers, the relationship between the nacelle anemometers of three adjacent turbines, V66 Turbines A, B, and C at Big Spring, to the nearby MET tower were examined. All three turbines are similarly exposed to prevailing winds and similar relationships were expected.

Figure 12 shows the relationship for each turbine, with the intercepts for each trendline set to zero to help illustrate the differences between the lines. The relationship between the MET tower and nacelle anemometers on Turbines A and C is close, while the relationship between the MET tower and nacelle anemometer on Turbine B is significantly different (with a slope varying by about 0.07). Assuming that the winds experienced by each turbine are similar, the resulting difference is most likely due to the inherent variation in the nacelle anemometers. The use of calibrated sensors would reduce the potential for this type of variation.

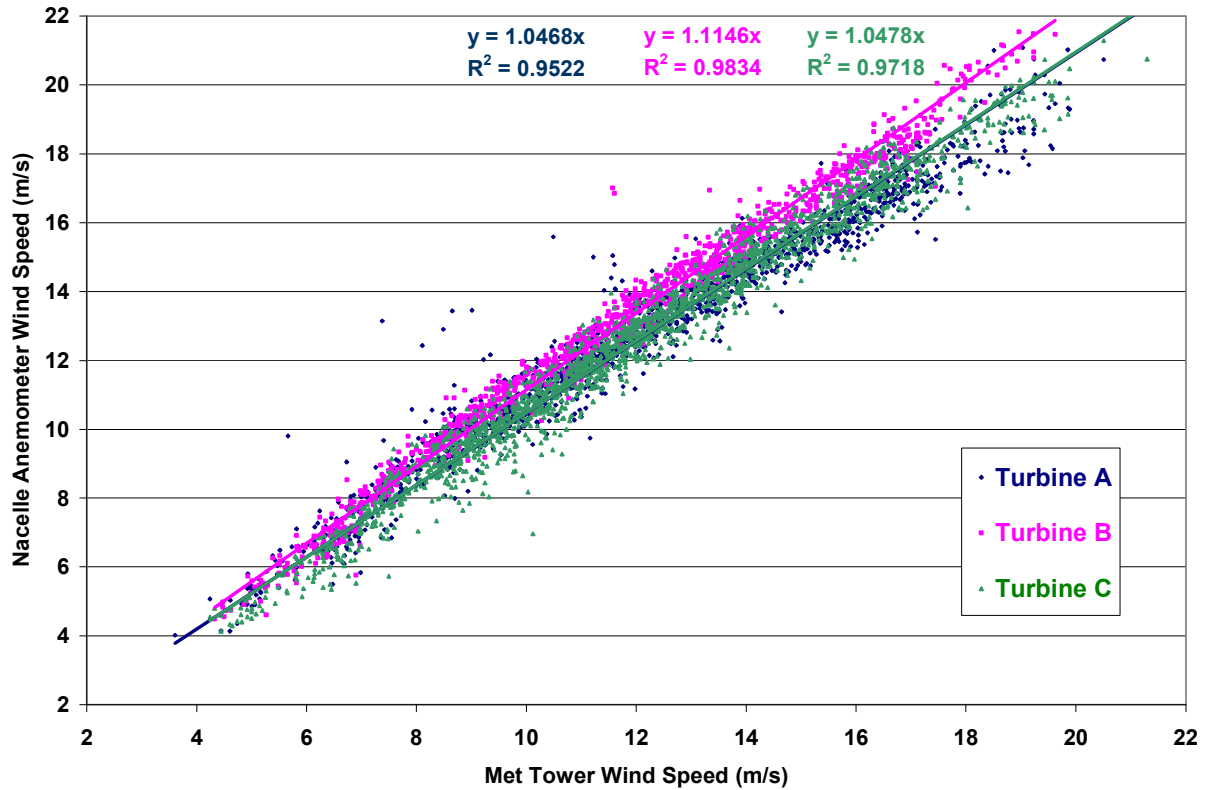


FIGURE 12: COMPARISON OF RELATIONSHIPS BETWEEN MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, BIG SPRING VESTAS V66 TURBINES A, B, AND C

To further evaluate the effects of uncalibrated anemometers, an additional analysis was performed with Big Spring V66 Turbine B. Shortly after completion of power performance testing of this turbine, the primary upwind MET tower anemometer failed and was replaced with an uncalibrated anemometer. Figure 13 illustrates the relationships between the MET tower wind speed measurements and nacelle anemometer wind speed measurements before and after the upwind anemometer was changed. As shown, the slope of the regression changed significantly – more than 0.05 – between the two time periods.

A power curve and AEP calculation was generated for V66 Turbine B based on the two relationships shown in Figure 13. The power curves are shown in Figure 14. The power curve based on the uncalibrated adjustment falls outside the uncertainty bounds of the results based on the MET tower throughout the body of the curve. Furthermore, the AEP using the uncalibrated measurements of 4.13 GWh/year is about 8.4% lower than the AEP based on the MET tower (estimated at 4.51 GWh/year). These results indicate the importance of using calibrated anemometers for power performance testing.

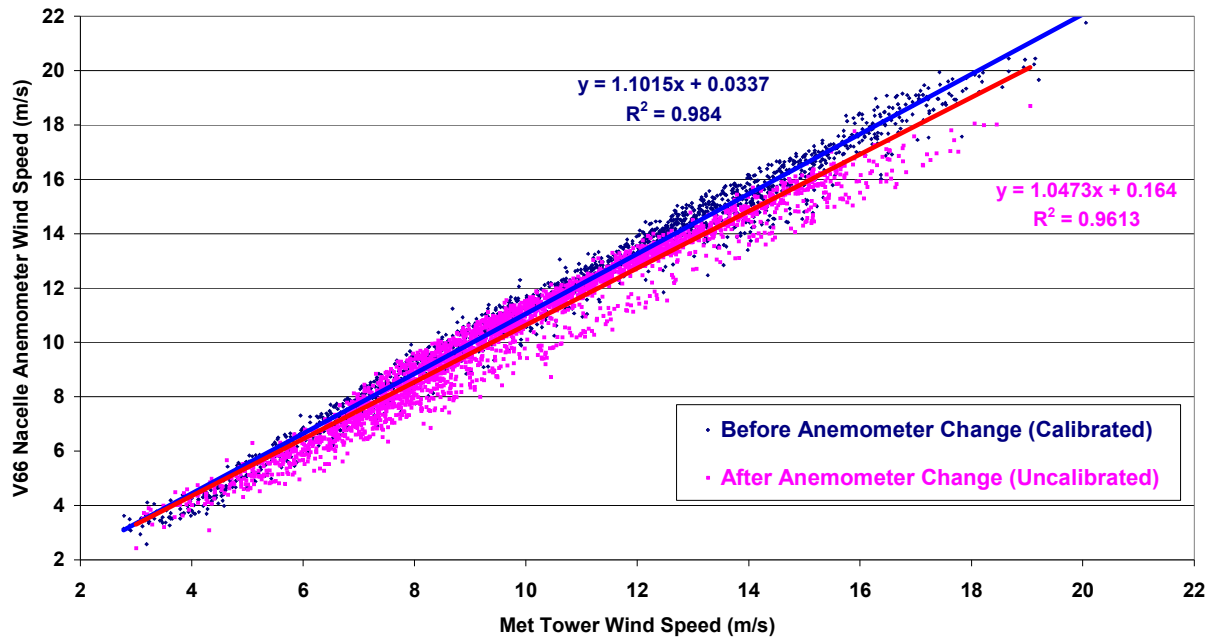


FIGURE 13: COMPARISON OF RELATIONSHIPS BETWEEN MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, BIG SPRING VESTAS V66 TURBINE B, BEFORE AND AFTER CHANGE TO MET TOWER ANEMOMETER

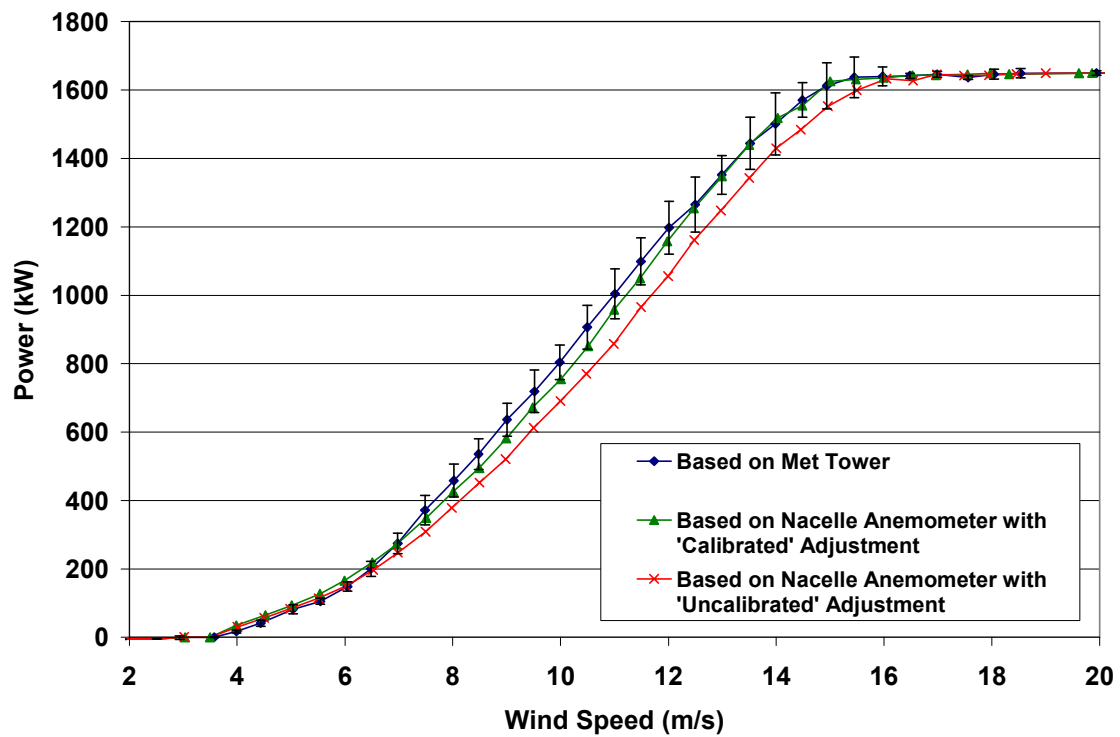


FIGURE 14: COMPARISON OF POWER CURVES, BIG SPRING VESTAS V66 TURBINE B

Turbine Control Issues

At the Nebraska TVP project, the turbines were repitched and the control software was adjusted to help improve turbine performance after the completion of the initial IEC power performance measurements. As a result, test data is available from the turbine for the periods before and after these adjustments were made. Figure 15 shows the relationship between the nacelle anemometer and the MET tower before and after the adjustments. Although the regressions are similar, the variation indicates that changes in turbine configuration can result in inaccurate measurements of free-stream wind speed and reduce the accuracy of the power curve estimates.

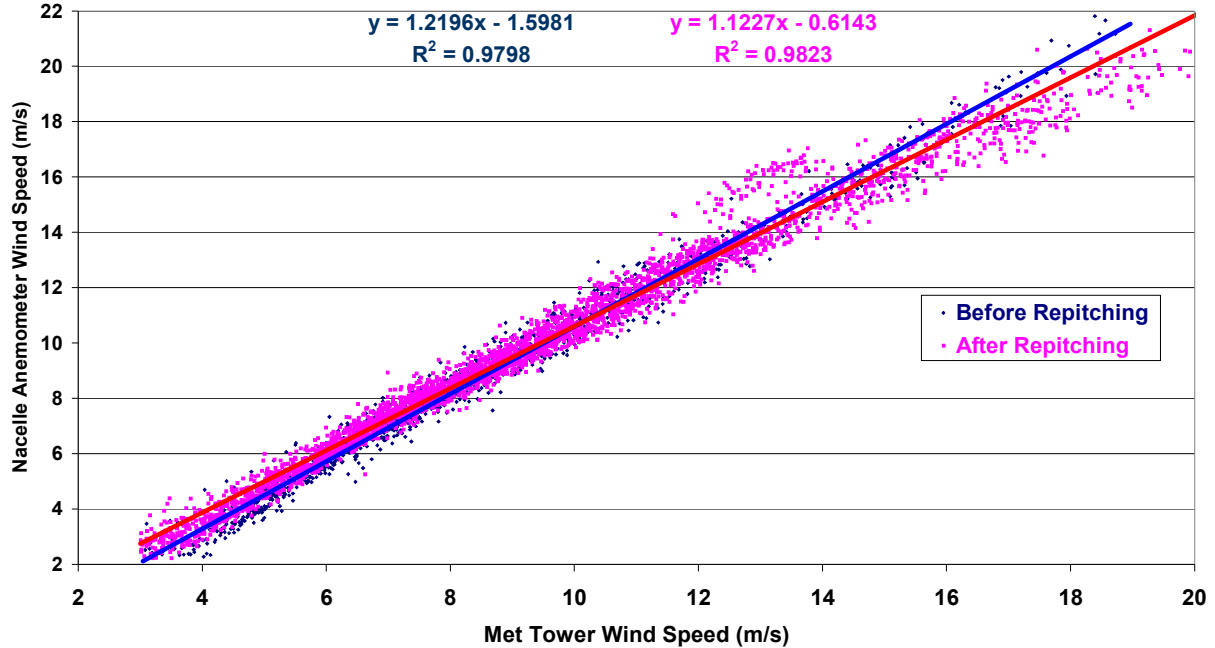


FIGURE 15: COMPARISON OF RELATIONSHIPS BETWEEN MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, NEBRASKA Z-50 TURBINE 1, BEFORE AND AFTER REPITCHING OF TURBINE

Non-Linear Relationships

In some cases, a linear regression may not appear to adequately describe the relationship between the sensors. For example, in Case 1, the relationship for the V47 varies from linear at high wind speeds. To determine if methods other than linear regression would more adequately describe the relationship between the anemometers, other approaches were investigated. Figure 16 illustrates the impact of grouping data for the V47 into 0.5 m/s bins. In this example, the ratio of nacelle anemometer to MET tower wind speed measurements was calculated for each bin. Power curves using the bin ratios to adjust nacelle anemometer measurements are shown for the V47 in Figure 17. As seen in this figure, no significant improvement in results is observed using the binned ratios.

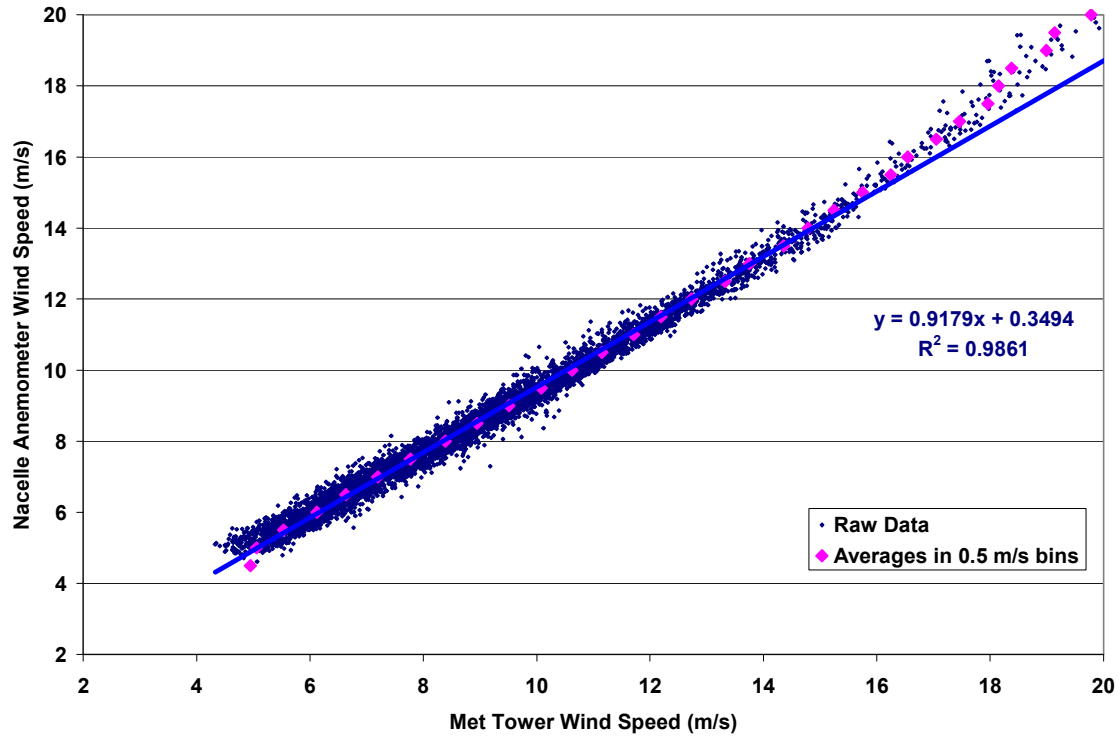


FIGURE 16: REGRESSION AND BINNED RATIOS OF MET TOWER AND NACELLE ANEMOMETER WIND SPEEDS, BIG SPRING VESTAS V47 TURBINE 26

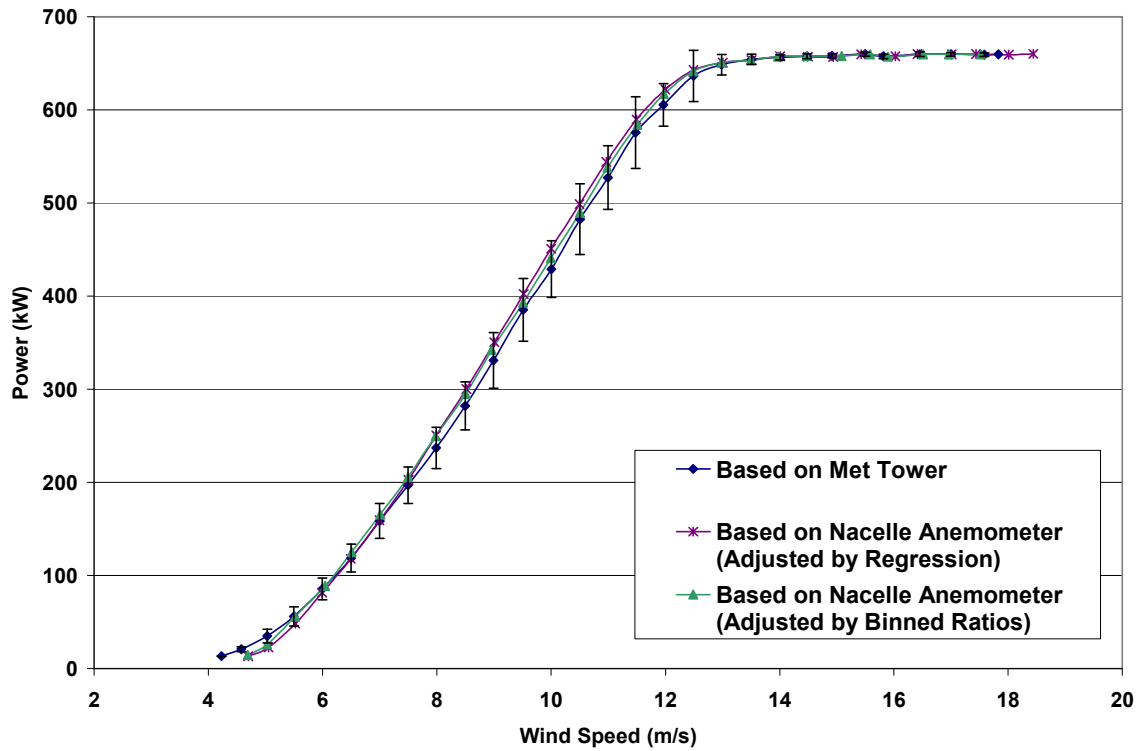


FIGURE 17: COMPARISON OF POWER CURVES, BIG SPRING VESTAS V47 TURBINE 26

The results using binned ratios applied to V47 Turbine 40 also showed no observable improvement in results. Use of a third-order regression was also evaluated, and results were similar. Consequently, we concluded that the linear regression was adequate for description of the ratio between nacelle anemometer and MET tower wind speeds for the turbine types investigated in this paper.

CONCLUSIONS AND RECOMMENDATIONS

Initial results using both the V47 and Z-50 wind turbines indicate that nacelle anemometers can provide reasonably accurate approximations of turbine power curves measured using upwind MET towers. Specific observations and conclusions include the following:

- The relationship observed between wind speeds measured at an upwind MET tower and a nacelle anemometer can be used to generate power curves for a test turbine with fairly low error in AEP estimates.
- Relationships observed for individual test turbines appear representative of other turbines of the same type, although uncertainties of approximately 3% in AEP estimates appear likely due to variations in these relationships. The method using nacelle anemometers appears to be sufficiently accurate for broad monitoring of turbines across a wind farm to verify that individual turbines are performing per specifications and to document that turbine performance remains constant over time.
- The most significant source of variation in these relationships is likely to be caused by the use of uncalibrated nacelle anemometers, although other sources of uncertainty may include differences in turbine controls, topographic variations near the turbines that could produce different wind flow around the nacelles, minor differences in anemometer mounting, and others.
- The relationships between wind speeds at the upwind MET tower and at the nacelle anemometers appear close to linear over most wind speeds, with the most variation at low (i.e., below cut-in) and high wind speeds. For the purposes of power performance testing, errors at high and low wind speeds are unlikely to have significant effects because at these speeds the turbines are either not online or are maintaining rated power.
- Much less scatter was observed in the power curves generated from the nacelle anemometers than from the power curves generated by the upwind MET towers. This increased precision in results suggests that if the relationships between the free-stream and nacelle wind speeds can be reliably determined, then the nacelle anemometers may produce more accurate power curves than using MET towers in complex terrain, where the upwind measurements may not be representative of free-stream winds at the turbine rotors.
- Maintaining a constant test turbine configuration is crucial for accurate power curve results using nacelle anemometers. Changes in controls, pitch settings, nacelle anemometer mounting, and blade condition could all significantly affect power curve estimates.

Based on these initial results, the use of nacelle anemometers for power performance testing appears promising and future research into these methods is warranted to better define procedures and understand potential drawbacks. Recommendations to further develop and improve the methodology include the following:

- Perform additional tests using calibrated anemometers on both the nacelles and MET towers to determine the impact of using calibrated sensors and identify if additional sources of uncertainty (such as topographic effects or variations in turbine configuration) can be isolated. The TVP is investigating if calibrated sensors can be installed on the test turbines evaluated in this analysis.

- Continue evaluation of additional turbine types and configurations to determine whether results are similar for different machines. Evaluation of fixed-pitch, stall-regulated turbines that do not maintain a constant regulated power may show that the methodology is inadequate for accurate determination of high wind speeds.
- Perform tests on turbines at a location where installation of an upwind MET tower is not practical to determine if the relationships established at other locations appear to apply. The TVP is planning to conduct such testing on the three V47 turbines at the TVA Buffalo Mountain wind project in Tennessee. The results of this testing will help indicate whether the relationships apply across sites and whether steep upwind terrain significantly affects wind flow around the nacelle anemometers.
- Encourage the IEC to complete development of a standard addressing use of nacelle anemometers to verify turbine power performance. This standard would formalize a methodology applicable across all wind energy facilities, including stand-alone turbines and wind farms, and provide guidance for power performance testing at sites in complex terrain.

ACKNOWLEDGEMENTS

The authors of this paper wish to acknowledge the management at NREL and U.S. Department of Energy for encouragement and approval of the time necessary to perform the analysis, paper preparation, and attendance at AWEA's WindPower 2002 conference. GEC's work was performed in support of the Wind Turbine Verification Program through DOE contract number YCX-1-31222-01. We would also like to acknowledge the project operators from which data utilized in this paper was obtained. TVP project operators include York Research Corporation (Big Spring, TX), Nebraska Public Power District (Springview, NE), and Algona Municipal Utilities (Algona, IA).

REFERENCES

1. *Wind Turbine Generator Systems, Part 12: Wind Turbine Power Performance Testing*, IEC 88/85/FDIS, Project 88/61400-12, International Electrotechnical Commission, Netherlands, 1998.
2. VandenBosche, J., McCoy, T., Rhoads, H., McNiff, B., Smith, B. *Power Performance Testing Activities in the DOE-EPRI Turbine Verification Program*. WindPower 2000 Proceedings, AWEA, Palm Springs, CA, May 2000.
3. Smith, B., Randall, G., VandenBosche, J., McCoy, T. *Power Performance Testing Progress in the DOE-EPRI Turbine Verification Program*. WindPower 2001 Proceedings, AWEA, Washington, DC, June 2001.
4. McGowin, C., Hall, T., Smith, B. *DOE-EPRI Turbine Verification Program (TVP)*. WindPower 1998 Proceedings, AWEA, Bakersfield, CA, May 1998.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 2002		3. REPORT TYPE AND DATES COVERED Conference Paper
4. TITLE AND SUBTITLE Applicability of Nacelle Anemometer Measurements for Use in Turbine Power Performance Tests: Preprint				5. FUNDING NUMBERS WER2.4710
6. AUTHOR(S) B. Smith, Hal Link, G. Randall, and T. McCoy				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/CP-500-32494
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161				12b. DISTRIBUTION CODE
13. ABSTRACT (<i>Maximum 200 words</i>) Collection of accurate wind speed data is one of the more problematic elements in conducting wind turbine power performance tests. IEC 61400-12 specifies meteorological tower placement between two and four rotor diameters upwind of the test turbine. However, use of an upwind meteorological tower can be difficult at some sites. In some cases, complex terrain near the turbine may make placement of an upwind tower impossible. In addition, purchase and erection of a meteorological tower can be expensive, particularly as the hub height of large turbines increases. Because of these concerns, wind farm owners and turbine manufacturers have expressed interest in the use of turbine nacelle-mounted anemometers for collection of wind speed data. The U.S. Department of Energy (DOE)-Electric Power Research Institute (EPRI) Wind Turbine Verification Program (TVP) has performed data collection and power performance tests at wind energy facilities located in the United States. The purpose of this paper is to evaluate the data gathered from the Big Spring, Texas; Algona, Iowa; and Springview, Nebraska, facilities to determine whether a meaningful relationship can be derived between meteorological-tower and nacelle-anemometer wind speed measurements for Vestas V47 and V66 turbines (Big Spring) and Enron Z-50 turbines (Algona and Springview).				
14. SUBJECT TERMS wind energy; wind turbines; wind turbine performance testing; nacelle; anemometer				15. NUMBER OF PAGES
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified		18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified		19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified
				20. LIMITATION OF ABSTRACT UL